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TITLE: Drought and Plant Leaf Reflectance of Southern California Vegetation Types

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DROUGHT AND PLANT LEAF REFLECTANCE OF SOUTHERN CALIFORNIA VEGETATION TYPES

Submitted by:

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INTRODUCTION

This investigation was undertaken to observe reflection from the vegetation of the hill lands of the San Bernardino-Riverside area, particularly that of chaparral. The purpose of the series of observation was to observe seasonal changes in color useful in determining the state of the vegetation, particularly in relation to drouth.

The observation schedule had been intended originally to be carried out by students, on a routine basis over a traverse of selected sites, and at different times of the year. Experience soon showed that such a program was premature, because of many problems connected with equipment, film, and monitoring devices that had not been fully anticipated. As a consequence, the program became one of primary investigation, and the observational material was used diagnostically, rather than statistically. Experiments in many aspects of photography with color infrared film were initiated and repeated by Dr. R. W. Pease during the course of the academic year 1967-68. Dr. H. P. Bailey made several dozen trips into mountain areas alone in some cases, and with Dr. Pease in others, for the purpose of taking pictures and measuring reflectance electrically with a broad-band spectroradiometer designed and constructed by Dr. Pease. Late in the year it became possible to use a selective spectroradiometer (ISCO Model SR) for measurement of both incoming solar and sky light, and for the reflected light from vegetation surfaces.

This report is thus primarily the joint product of the two primary investigators of the contract, and has required less student assistance than had been anticipated. The results and recommendations of the study,

however, point out how future investigations can be carried out to improve measurements of reflectance from vegetation, and their possible implications in forest management.

PRINCIPLE OF THE VISUAL INTERPRETATION OF LIGHT REFLECTED FROM NATURAL SUBSTANCES.

The eye perceives color in natural surfaces exposed to sunlight according to A) the spectral characteristics of the illumination (the source), B) the reflectance characteristics of the surface being examined as they are described in terms of spectral intensity (the input to the eye or camera), and C) the spectral sensitivity of the responding medium (the response of eye, film, or meter). Step C is multiple if the eye is used to interpret color film, in which case the spectral response of the film to the camera input prepares an image which is interpreted by the eye according to its spectral sensitivity.

It is thus not relevant to assign significance to a color difference from one object to another, or that observed in the same object at one time as compared to another, without keeping track of the chain described by the source-reflectance-response linkage. Each of the links will be briefly reviewed.

A. Spectral characteristics of light from the sun and sky

The temperature of the surface of the sun is measured to be close to 6,000 deg K, and curves of its emission are often prepared on the basis of black-body emission at that temperature according to Planck's equation. However, the effects of absorption within the solar atmosphere, and by the earth's atmosphere, chiefly by ozone and water vapor, serve to eliminate light shorter in wavelength than the 290 nanometers, and to reduce the

intensities of light in other, narrower spectral zones (Fig. 1). In addition, selective scattering of blue light within the atmosphere tends to reduce the blueness of solar light. Eastman Kodak Company rates the effective color temperature of the noon-day sun as 5400 deg K. and light from the blue sky as well over 10,000 deg K.

Color temperatures of the sun and sky vary considerably according to time of day and turbidity of the atmosphere. We have measured the color temperature of the sun as high as 5800 deg, but the minima fall well below 5000. Sky light is stated by EK to vary between 12,000 to 18,000 deg.

Obviously, the colorometric quality of light from the sun and sky is far from constant, and so must be taken into account as a primary variable in interpretation of images or photometric measurements of objects with natural illumination. Although intensity of light as such does not affect color quality, intensity does become a variable in interpretation of objects on color film when it falls to levels so low as to alter the reciprocity relations of the dye layers. In dim light CIR film tends to become somewhat green in color balance.

B. Reflectance

Spectral reflectance curves of two typical foliage types are shown in Figure 2. Foliage of many sorts shows a maximum in the range between 500 to 600 nanometers, corresponding to light in the range seen as green by the human eye. A second and much higher peak occurs at 700 nanometers, and beyond, above the range of human vision. This strong reflection in the near-infrared is the light recorded by ordinary "infrared" film, both in uncolored and colored versions. It should be emphasized that the phenomenon

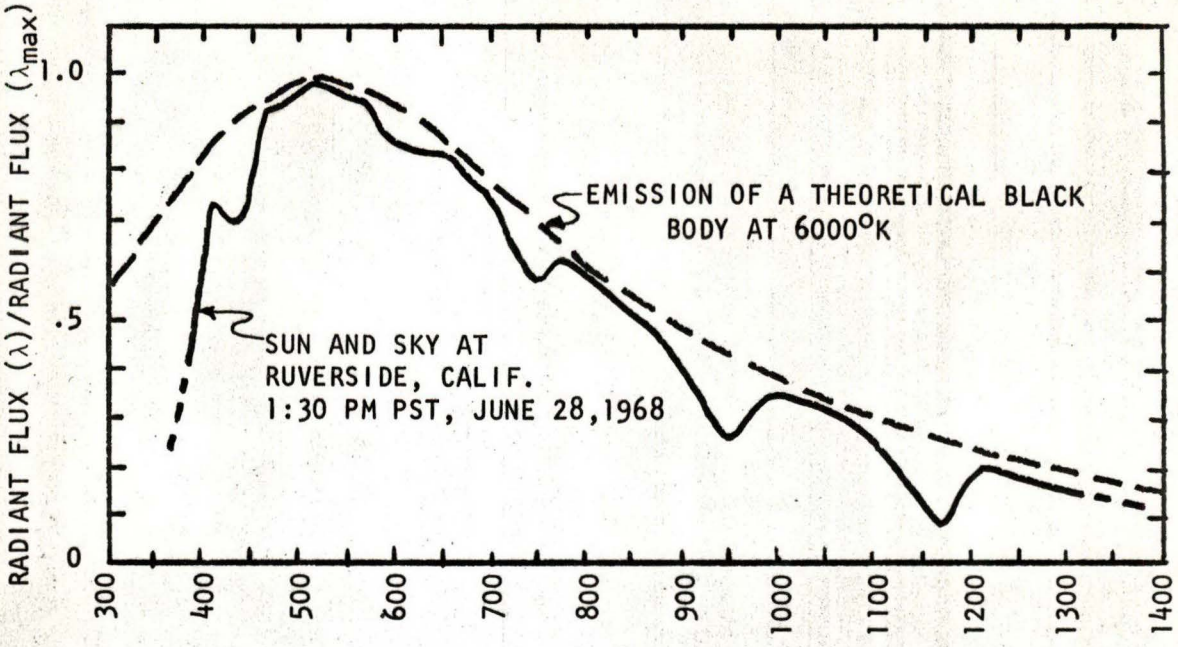
Figure 1. SOLAR ILLUMINATION

a. Sunlight falling on a horizontal surface at Riverside, California compared with the emission of a theoretical black body with a temperature of 6000°K. Major differences are (A) sunlight at the earth's surface has lost most energy with wavelengths shorter than 400 nanometers due to atmospheric absorption of the ultraviolet and (B) absorption dips occur both near the solar peak (due to Fraunhofer lines from the solar atmosphere) and in the infrared due to water vapor in the earth's atmosphere.

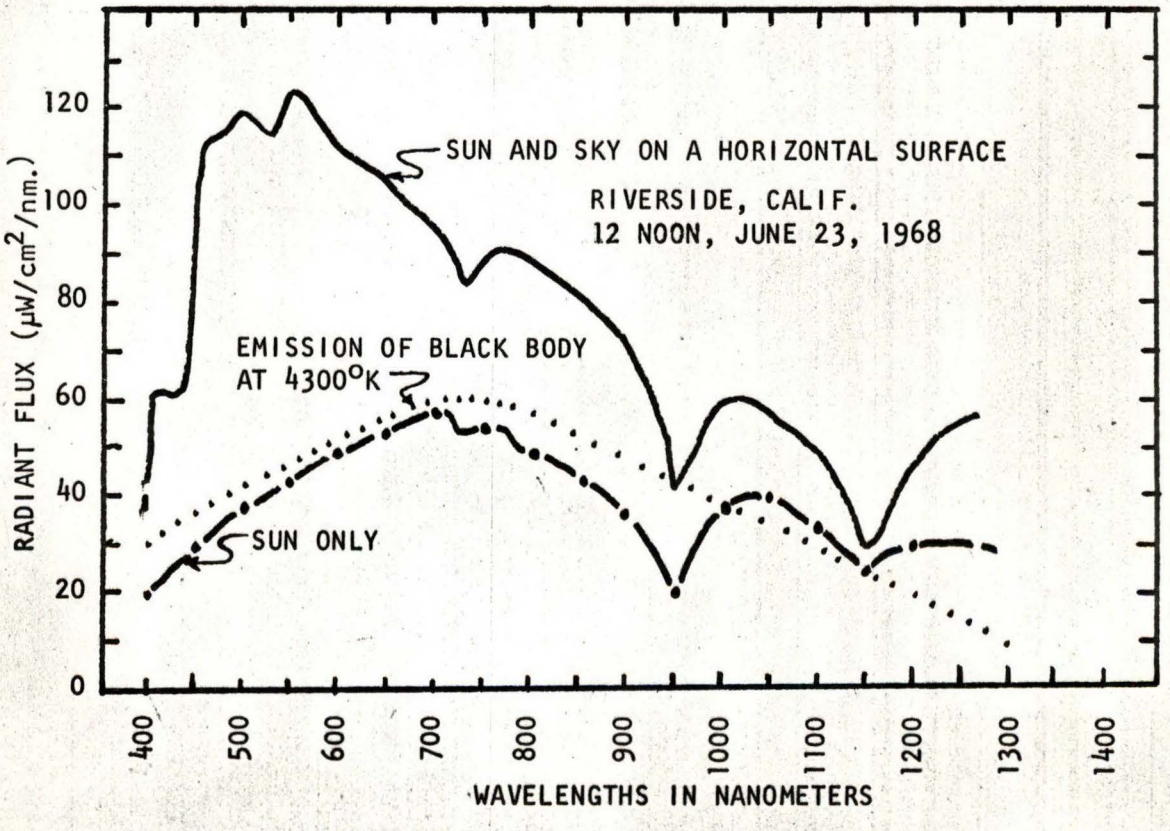
The sunlight curve was measured with an ISCO spectroradiometer and the black body curve is according to a General Electric Radiation Calculator.

b. Sunlight (sun and sky) versus sun alone. Although sunlight falling on a horizontal surface may come close to a color temperature of 5500-6000°K, the direct sun rays may have a color temperature that is considerably lower. In this example measured at Riverside, California, the sun rays in mid-day approximated a color temperature of only 4200°K. The sun rays were penetrating a layer of marine air approximately 4500 feet in thickness with selective scattering of the short wave component of the direct radiation. Above or without the marine layer, solar color temperatures as high as 5900°K have been measured.

FIG. 1.


RADIANT FLUX (λ)/RADIANT FLUX (λmax)
1.0
.5
0
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
EMISSION OF A THEORETICAL BLACK BODY AT 6000°K
SUN AND SKY AT RUVERSIDE, CALIF. 1:30 PM PST, JUNE 28,1968

a.


RADIANT FLUX (μW/cm²/nm.)
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100
80
60
40
20
0
400
500
600
700
800
900
1000
1100
1200
1300
1400
WAVELENGTHS IN NANOMETERS
SUN AND SKY ON A HORIZONTAL SURFACE
RIVERSIDE, CALIF.
12 NOON, JUNE 23, 1968
EMISSION OF BLACK BODY AT 4300°K
SUN ONLY

b.

Figure 2. PLANT LEAF REFLECTANCE

Reflectance is a property of a given specimen of plant material at any given time. It is independent of the spectral distribution of the illumination. For healthy leaf tissue it is generally low in the visual realm but relatively high in the near infrared. The infrared reflectance generally declines above 1200 nanometers when the tissue again becomes highly absorptive. On reflectance curves, the green peak near 500 nanometers appears low in comparison to the infrared peak. The latter, however, is invisible to the eye whereas the green is both accentuated by the spectral distribution of sunlight and the spectral sensitivity of the human eye.

These reflectance measurements were made with an ISCO spectro-radiometer. For incident illumination the diffusing surface of the instrument was placed in a horizontal position. To measure the plant reflection a mass of leaves was placed against a non-reflective background (Plate 2) and a special field reducing device designed by the authors kept out extraneous reflections.

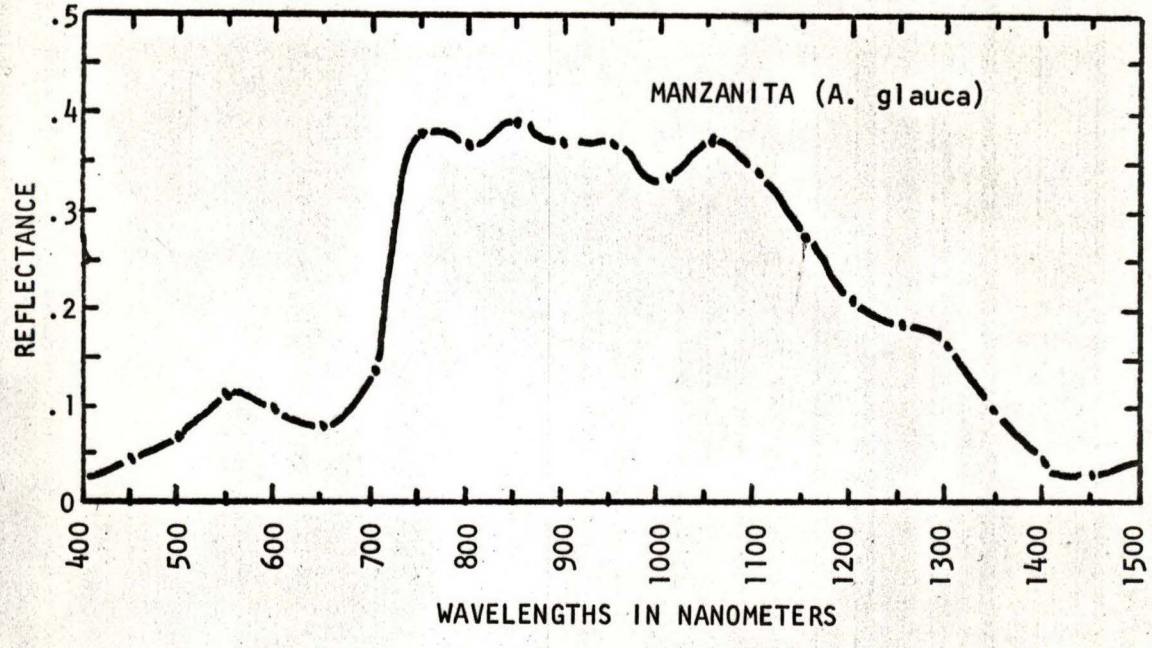
a. Manzanita leaves (Arctostaphylos glauca) secured from Lone Pine Canyon in the San Gabriel mountains from an elevation of 3700 feet.

b. Yellow pine leaves (Pinus Jeffreyi) secured from Crestline in the San Bernardino Mountains.

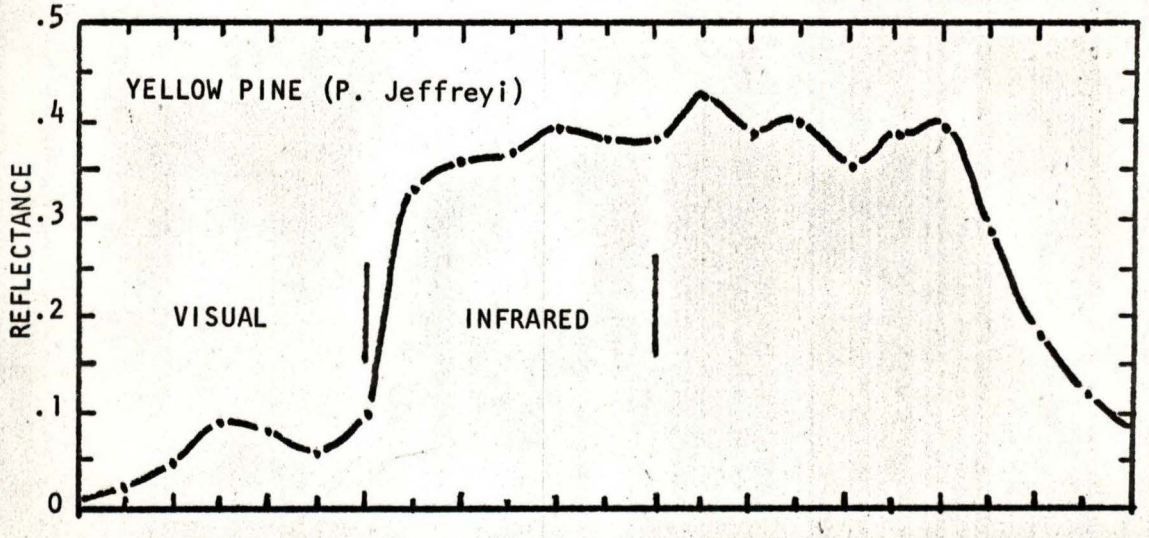
The "visual" and "infrared" notations and the accompanying vertical lines show the approximate bands sensed by the broadband spectro-radiometer.

Specimens were secured close to July 1, 1968.

FIG. 2.


MANZANITA (A. glauca)
REFLECTANCE
.5
.4
.3
.2
.1
0
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTHS IN NANOMETERS

a.


YELLOW PINE (P. Jeffreyi)
REFLECTANCE
.5
.4
.3
.2
.1
0
VISUAL
INFRARED

b.

is one of reflection, not emission, and so pertains to photography only when daylight or some other source of appropriate illumination is available.

One of the primary goals of this project has been to observe spectral changes in reflectance due to seasonal effects upon native chaparral vegetation. In particular, changes in infrared reflectance of plant leaves have been a matter of concern.

C. Response of Color Infrared Film

Kodak Ektachrome Infrared Aero Film, Type 8443, has been used in this investigation. Its characteristics have been described in several publications. It renders color falsely. Light in the near infrared, from 700 to 900 nanometers, is made visible by an appropriately sensitized cyan-forming layer in the film, which with the other two dye layers (magenta and yellow) providing the color, converts the non-visual infrared to visual red. So that it will not be confused with the near infrared and a neutral balance be possible, visual red is rendered green by a magenta-forming layer, and the visual green is rendered blue by a yellow-forming layer. In this manner, the film reproduces colors in the same sequence as normal color film, but in relation to input, one color "block" toward longer wavelengths. To block the cyan layer's sensitivity to blue and thus prevent confusion from light that originates in this waveband, a yellow filter is used with the camera that does not transmit below 500 nanometers. Nevertheless, it is typical that the sky is rendered blue by CIR film because the Rayleigh scattering effect is strong enough in the green to be "moved over" into the blue "block" of the film.

When the reflectance characteristics of a subject are known, it is

possible to predict the color rendition of CIR film by taking into account the spectral responses of each dye layer, which incidentally overlap to a considerable degree. This interpretation is complicated by the fact that natural substances usually reflect light over a wide range of wavelengths, and thus affect all dye layers to a greater or lesser degree. The intensity of the illumination at the various wavelengths interacts with the reflectance of the subject at those wavelengths to yield the spectral distribution of energy that exposes the film (Fig. 3). In the case of subjects illustrated in Figure 2, however, it is not difficult to predict color rendition for infrared reflectance is so overpowering that foliage is typically seen on CIR film as red.

The eye responds to light in a manner very nearly matched with the solar spectrum. The wavelength of maximum energy emitted by the sun lies close to 480 nanometers, and the eye is most sensitive to radiation at 550 nanometers. The relative response of the eye to radiation over the span of human vision is given in Table 1. The numerals given in the table may be viewed as weighting factors of discount which preferentially weight human color perception toward the green. Obviously, the minor maximum in green reflectance by normal foliage is then emphasized both by human perception and the nature of the solar spectrum. It follows that small changes in the quality of green light will be perceived more readily than equivalent changes in other wavelengths.

TABLE 1 - 1924 CIE Luminosity Factors

Wavelength in mμ	Luminosity Weighting Factor	Wavelength in mμ	Luminosity Weighting Factor
380	0.0000	580	0.8700
390	.0001	590	.7570
400	.0004	600	.6310
410	.0012	610	.5030
420	.0040	620	.3810
430	.0116	630	.2650
440	.0230	640	.1750
450	.0380	650	.1070
460	.0600	660	.0610
470	.0910	670	.0320
480	.1390	680	.0170
490	.2080	690	.0082
500	.3230	700	.0041
510	.5030	710	.0021
520	.7100	720	.0010
530	.8620	730	.0005
540	.9540	740	.0003
550	.9950	750	.0001
560	.9950	760	.0001
570	.9520		

Figure 3. REFLECTION VS REFLECTANCE

Reflection is the actual energy being reflected from an object, in this case plant leaves. The energy reflected will have a special distribution that depends upon the reflectance properties of the plant material and the spectral distribution of the illumination. Since it is the reflection that exposes film or actuates a measuring meter, the relationship of reflectance to the spectral distribution of illumination must be kept in mind.

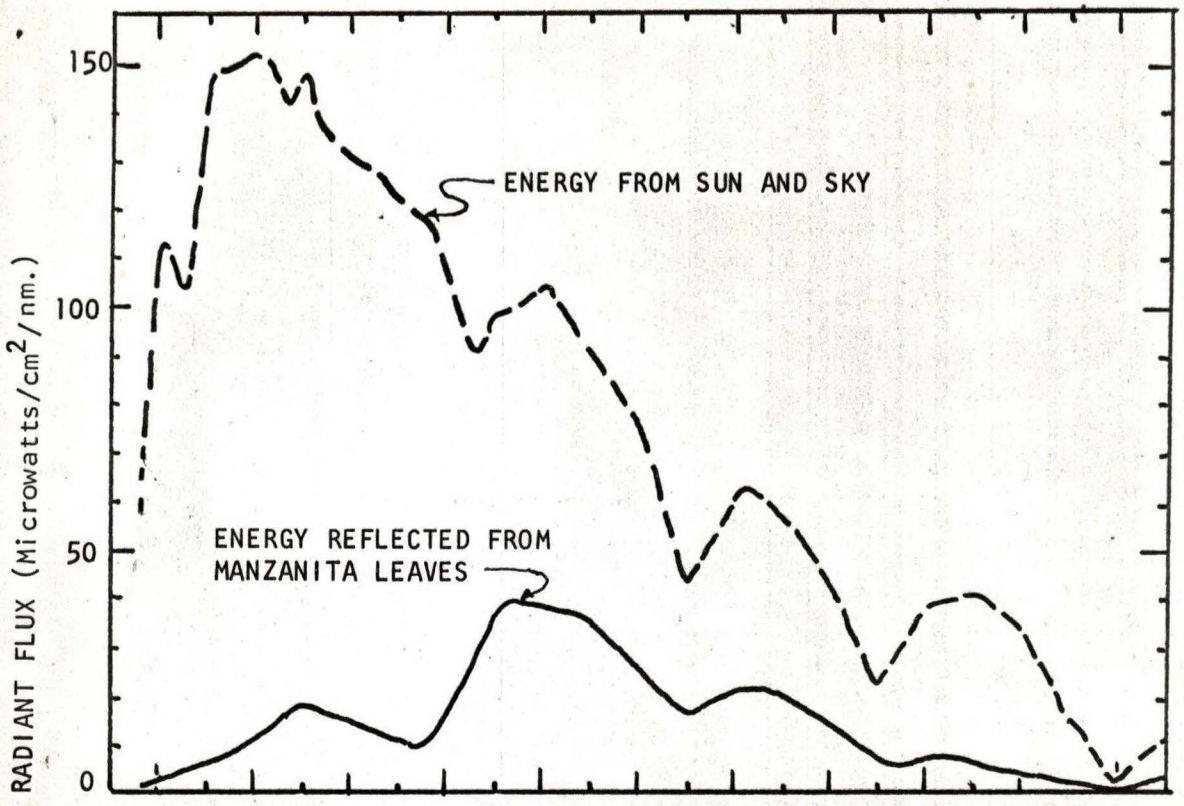
a. Incident illumination and that portion of it reflected by manzanita leaves (A. glauca) is plotted according to wavelength. The fractions of the incident illumination that are reflected at the various wavelengths permit measurements of the property of reflectance.

b. A comparison of reflection and reflectance for Manzanita leaves. Both curves have been plotted so that values at 750 nanometers coincide. It will be noted that the spectral nature of sunlight illumination accents the green reflection at "A" but depresses the infrared reflection at "B."

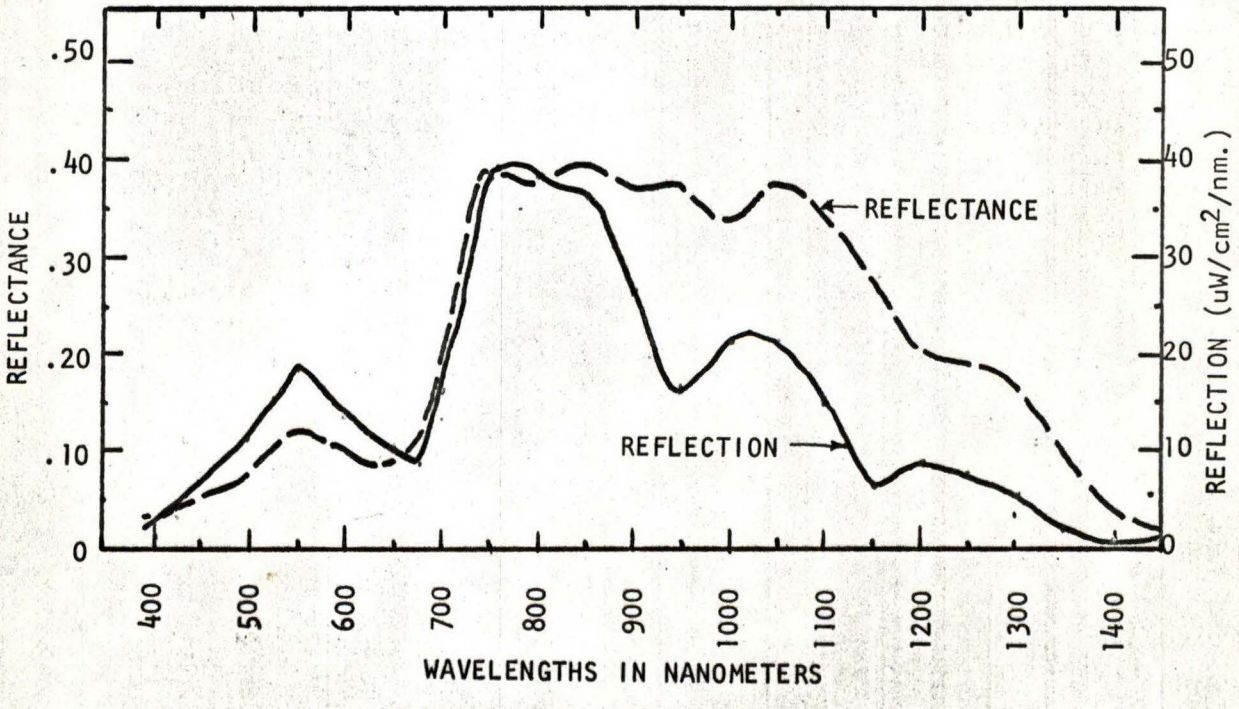
The fact that reflectance is independent of illumination makes its use more consistent for reflection comparisons between different sites and at different times. Since CIR film depends upon actual reflected energy (reflection) results will be affected by differences in the spectral distribution of the illumination.

Curves plotted from measurements made with an ISCO spectro-radiometer.

FIG. 3.


150
100
50
0
RADIANT FLUX (Microwatts/cm^2/nm.)
ENERGY FROM SUN AND SKY
ENERGY REFLECTED FROM
MANZANITA LEAVES

a.


.50
.40
.30
.20
.10
0
REFLECTANCE
50
40
30
20
10
0
REFLECTION (uW/cm^2/nm.)
REFLECTANCE
REFLECTION
400
500
600
700
800
900
1000
1100
1200
1300
1400
WAVELENGTHS IN NANOMETERS

b.

TRANSMISSION CHARACTERISTICS OF THE ATMOSPHERE.

Clear, dry air transmits energy of solar wavelengths without major alterations, except for the removal of the ultraviolet by ozone (wavelengths 290 nm and less), and selective scattering by atmospheric particles (Rayleigh scattering). As the latter varies inversely as the fourth power of the wavelength, much more blue light is scattered than red, and wavelengths beyond 700 nm are affected least of all (in the range between 500 and 900 nm pertinent to this discussion). By eliminating wavelengths below 500 nm by use of a minus-blue filter, (Wratten 12 or 15) the blue haze created by scattering (the "air light" in visual range theory) does not affect color IR film. Scattering between 500 and 600 nm is still effective enough to produce the blue color rendered by the film of clear-sky subjects, but the blue is notably darker in general than is true of skies usually seen on Ektachrome or Kodachrome Film.

Type 8443 film is balanced by the manufacturer to give optimum results with the sun more than two hours above the horizon, and for subjects within 1000 feet of the camera. Subjects in shadows are illuminated by so little light affecting CIR film that they are usually very dark. Even when subjects are far away the darkness of shadows is maintained because of the lack of response of the film to blue light that is scattered in the air space between subject and camera, as mentioned previously. This characteristic is responsible for the crispness of outline between light and shade so typical of images rendered by CIR film.

Two variables act as controls of the strength of the infrared record in addition to the reflectance characteristics of the subject. First, is the

relative amount of near infrared in the illumination. For the sun this varies with the altitude of the sun as has been noted. Second, near infrared wavelengths reflected by the subject may be depleted by a long traverse through the atmosphere to the camera. Here two phenomena play important roles. Water vapor in the air provides absorption bands above 700 nanometers and the nature of the Rayleigh scattering (above 500 nanometers) also decreases the relative exposure of the infrared component. Depletion of near infrared wavelengths in sunlight illumination is minimized by photography with the sun as near as possible to the noon altitude. Depletion between the subject and camera is minimized by photography at close distances. When near infrared wavelengths (700 to 900 nm) are depleted by long light paths, vegetation which appears strongly red when photographed at close range weakens in redness with increase of distance, the red often becoming purplish brown. Since it is desired that the infrared record show changes in the health and vigor of vegetation, it is highly undesirable that variables other than plant reflectance be either eliminated or be entered into the interpretation of imagery. For this reason, attention has been paid in this investigation to attenuation of near infrared wavelengths as a function of length of light path.

The graphical and tabular information on water vapor absorption available to these investigators is not sufficient to establish precisely its effect on the performance of CIR film. However, the data available and our own spectro-radiometric measurements indicate that such absorption increases progressively throughout the 700 to 900 nm wave band, and with water vapor present in the light path a significant absorption band occurs at the longwave edge of the film's sensitivity. The effect of absorption differs from that of selective

scattering, because absorbed energy creates heat emitted at terrestrial temperatures at a level too low to affect CIR film. Hence, absorption by water vapor, or any other atmospheric substance, weakens the wave band affected, but does not create a secondary obscuring effect.

Selective or Rayleigh scattering above 500 nanometers also reduces the relative strength of the infrared in a long air path. Due to the fourth power decrease of the scattering with increasing wavelengths, air luminance is more effective in exposing the film in the realm of the spectral greens than in the near infrared. Reduction of exposure to combat this concomitantly reduces the exposure of the near infrared.

Non-selective scattering (Mie scattering) takes place when particles reach sizes equal to or greater than the wavelengths of light. A whitish haze results which is rendered white by CIR film; clouds and snow are also seen as white subjects. However, if an overcast is present through which white light is scattered, and this is the only source of illumination, (exposures determined by conventional photoelectric meters) shadow areas are illuminated and images seem flat and uninteresting. All effects of Mie scattered illumination have not been fully established.

REFLECTANCE MEASUREMENTS OF PLANT MATERIALS

Two methods of making quantitative observations were used. One employed a commercially available ISCO spectroradiometer (Instrument Specialties Co.) and the other a broadband spectroradiometer or photometer of our own design.

The ISCO instrument has a spectral range of 380-1550 nm and thus covers both the visual and near infrared wavebands. Although it reads out in microwatts /Cm^2 / 10 nanometers, the actual band width being sensed for any wavelength reading is 25 nm in the visual realm and 50 nm at longer wavelengths. Because of this it records only major absorption dips in the solar curve.

Development of reflectance curves with the ISCO involves (1) making a sequence of readings for incident illumination falling on the plant material, (2) making a sequence of readings of the energy reflected by the plant, and (3) setting up a ratio of reflected to incident illumination for each spectral point:

$$\text{Reflectance } (\lambda) = \frac{\text{Reflected energy } (\lambda)}{\text{Incident energy } (\lambda)} \qquad (1)$$

From this sequence a curve of reflectance for the plant material is constructed, a somewhat long and tedious process requiring more than an hour. It therefore does not lend itself well to multiple readings over a period of time. Each set requires its own incident light curve. To speed up ascertaining the simple relationship of visual to near infrared reflectance, a broadband spectroradiometer was designed and calibrated to the ISCO (see Appendix A). This instrument integrates all energy with wavelengths between 400 and 700 nm into a single reading produced by a selenium sensor operated in a photovoltaic mode. Similarly, energy between 700 and 1100 nm is sensed by a photovoltaic silicon solar cell. The silicon cell is placed behind a light filter with

a short wave cutoff at 700 nm. Its own sensitivity causes an upper cutoff essentially between 1000 and 1100 nm. The selenium cell is exposed directly to the light with the curve of sunlight cutting it off rapidly below 400 nm and its own sensitivity curve at 700 nm. The sensors are at the end of a tube (Plate 1) which restricts the angle of light acceptance to approximately 12°. Output from the two cells is fed selectively into a microammeter. One instrument was so trimmed that 1 microampere=200 microwatts /Cm^2/ 300 nm band. The energy available to the sensors under typical sun-sky illumination is shown in Fig. 4. By use of correction factors the sensor energies can be converted to wave band energies (400-700 nm and 700-1000 nm) for an illumination source of any color temperature. The correction factor for the instrument pictured for solar illumination (6000°K) was 1.00.

Using this instrument, much more rapid comparisons of visual and near infrared reflectances can be made. Like the ISCO, the instrument measures reflection, but readings can be converted to reflectances by taking incident light measurements from a standard reflectance card or using an incident light screen over the end of the radiometer of known transmission value. By using simple proportion to combine these with reflection measurements from the plant material, an integrated reflectance for the visual waveband and one for the near infrared can be quickly determining. For example, if an Eastman Kodak 18% reflectance card[1] is used to evaluate the incident illumination, the reflectance for the visual band (measured by the seleniums cell) would be determined as follows:

$$R_v = 0.18\ (r_{vp}/r_{vc}) \qquad (2)$$

[1] ISCO measurements showed the EK 18% and to have a reflectance variation of only ± 2% of the rated value between 400 and 1100 nm.

Where R_v is average reflectance for the visual band,

r_{vp} is the reflection from the subject, and

r_{vc} is the reflection from the 18% card.

Infrared reflectance can be determined in the same way, using the silicon sensor for the subject card.

An attempt was made to calibrate another version of the instrument to measure reflectance directly. Such a calibration restricts meaningful measurement to sunlight illumination and this is only approximate due to spectral differences of sunlight under various atmospheric conditions and with the sun at differing altitudes.

DROUGHT AND PLANT REFLECTANCE

The use of plant reflectance as an indicator of drought appears predicated upon the effect of tissue water content upon this property. There is a prevalent notion that the high infrared reflection of plants is due to water in leaf tissues. However, some workers in this field have suggested rather that it is the visual reflectance that drops as water in tissue increases.

The reflectance curves (Fig. 4) for yellow pine (P. ponderosa) needles in various stages of dessication suggest that loss of water content causes two basic changes to occur (Plate 2). First, the reflectance in the near infrared is mildly reduced particularly from 700-900 nm. Under sunlight illumination actual reflection is relatively less affected than reflectance since less energy is available in this waveband than in the visual. Second, as chlorotic decline occurs the visual reflectance is increased particularly between 600-700 nm, an effect that is enhanced by the spectral distribution of sunlight. In this inquiry, these changes were produced by the artificial

Figure 4. PLANT LEAF REFLECTANCES

Reflectance of the leaves of Yellow Pine needles under several conditions of dessication and that of Manzanita (Arctostaphylos glauca) are shown in the accompanying graphs. All were made with the ISCO spectroradiometer using sunlight illumination. Needles were collected near Crestline, California in July.

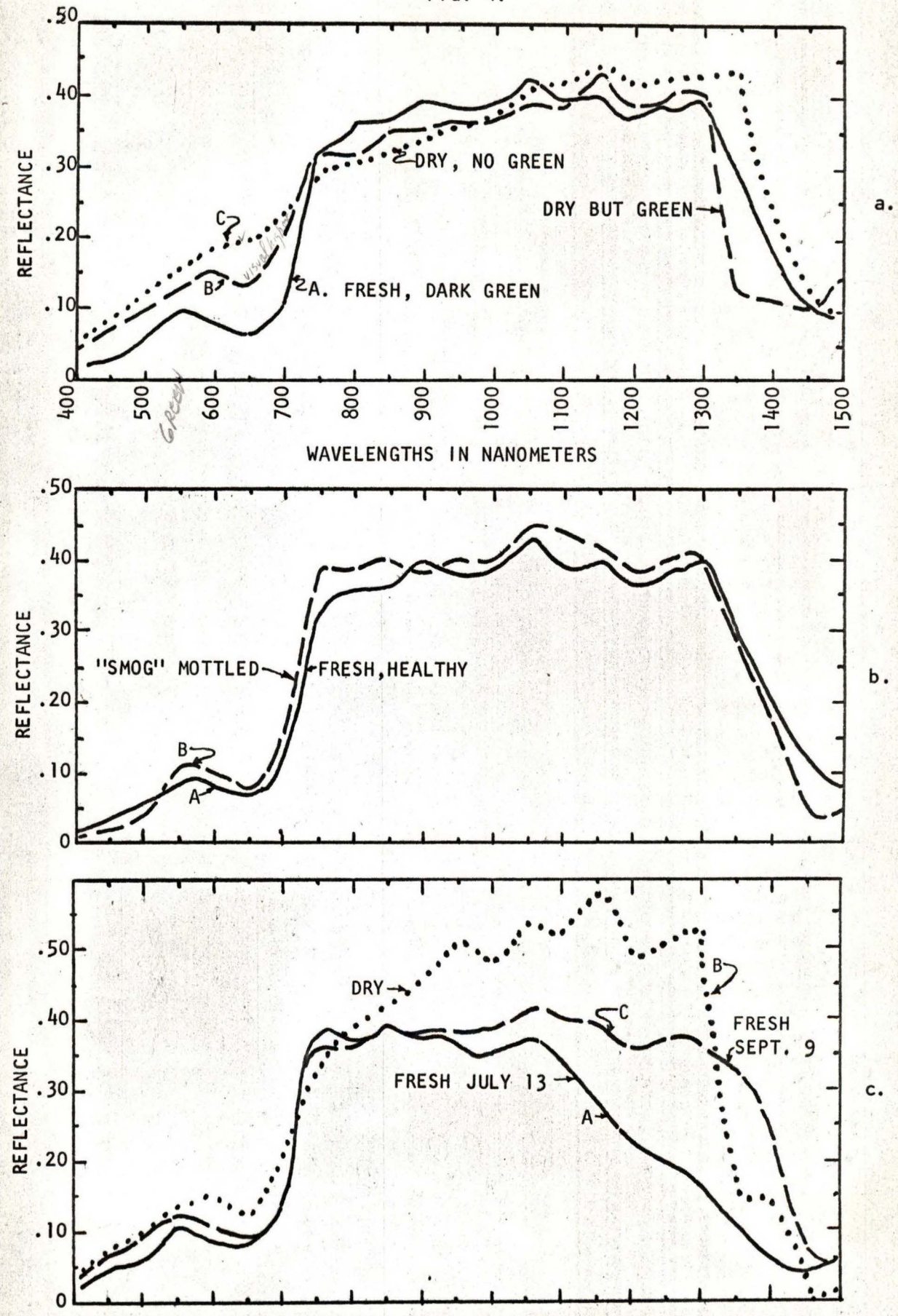
a. Yellow Pine needles in three stages of dessication and chlorotic decline. Fresh, healthy, and dark green needles (A) show the greatest depression of the visual reflectance (400-700 nm). Dry needles that are still green in color (B) still retain the green peak between 500 and 600 nm but the visual reflectance is higher than with the fresh needles. Needles that have been dry sufficiently long that the green coloration is mostly lost (C), a light straw color, have visual reflectances that rise more rapidly than the other two and which are particularly high in the waveband between 600 and 700 nm.

It should be noted that the infrared reflectance of needles in all three states is approximately the same. There is only a slight drop as the needle loses its green coloration. (As the dead needle weathers it darkens and lowers its reflectance in all wavelengths below 1000 nm). This suggests that the change in the VIS/IR reflectance ratio with dessication is due to a rise in the visual reflectance rather than a loss of infrared reflectance.

b. A comparison of healthy, dark green needles (A) with yellowish-green "smog" mottled needles from an adjacent tree. There is little difference in the reflectance curves.

c. Three samples of Manzanita leaves (A. glauca), from the same plant but subjected to different conditions of drought. Leaves measured while fresh on July 13, 1968 have the reflectance of curve A. The same leaf mass after three days of drying showed the reflectance of curve B. A small rise in the visual reflectance is to be noted, but the major change is the rise in the infrared for wavelengths longer than 900 nm. Fresh leaves from the same plant, measured later in the season (September 12, 1968) also showed considerable rise in the reflectance above 900 nm. Even though it might be an indicator of drought, a rise this deep into the infrared is beyond the sensitivity of infrared film and would require more sophisticated sensors for its measurement than were used in the broadband spectroradiometer.

FIG. 4.


.50
.40
.30
.20
.10
0
REFLECTANCE
DRY, NO GREEN
DRY BUT GREEN
C
B
A. FRESH, DARK GREEN
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
WAVELENGTHS IN NANOMETERS
a.
"SMOG" MOTTLED
FRESH, HEALTHY
b.
DRY
B
C
FRESH SEPT. 9
FRESH JULY 13
A
c.

drying of the plant material which may well more drastically reduce tissue water content than drought or in other ways not parallel the increase in tissue water stress that develops under growing conditions.

A procedure for studying the convergence of visual and near infrared reflectances with dessication has been the use of a "VIS/IR reflectance ratio." This was easily accomplished with the aid of the broadband spectro-radiometer by dividing the visual reflectance by the infrared reflectance.

$$\frac{Rv}{R_I} = \text{VIS/IR Reflectance ratio.}$$

Since in plant materials the infrared reflectance is typically 3 to 7 times as great as is the visual, typical ratios vary from .150 to .350. The ratio is used in this form, rather than its reciprocal because the infrared reflectance appears to vary least with water stress and chlorophyll changes. Thus the "VIS/IR reflectance ratio" connotes then the depression of the visual below an infrared datum. In essence we are comparing a variable visual reflectance to a more stable infrared reflectance.

Drying pine needles exhibited a consistently rising ratio as dessication proceeded. From .160 for healthy fresh needles, the ratio steadily rose to .326 as the needles dried out. Dry and brown needles had roughly the latter VIS/IR ratio.[2] Results with drying manzanita leaves (A. glauca) were not so conclusive. For mature leaves the ratio rose from .206 on the plant to .278 for the plucked leaves after 3 days of drying. New growth, however, showed much lower ratios (.157) on the plant, but the leaves wilted and turned brown rapidly after plucking making it difficult to ascertain a meaningful VIS/IR

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[2] It is to be noted that dry plant material still has a much higher infrared than visual reflectance (three times as great in this instance). The spectral distribution of energy of sunlight, however, tends to negate this as far as actual reflection of energy is concerned.

sequence.

To better assess VIS/IR ratio differences that might occur under growing conditions, observations over a short period of time were made of single species growing in sites with differing soil moisture. Exposure to sun and elevation were two parameters for making site choice. Chamise (Adenostoma fasciculatum) was checked under a variety of conditions within a timespan of a few hours on July 10, 1968 and in sites ranging from the alluvial fan of Cajon Creek (elev. 1500 feet) to Lone Pine Canyon (elev. 4300 feet). With one exception (a semi-riverine location), ratios decreased with elevation as shown in Table 2.

Table 2

Location	Elevation (feet)	VIS/IR Reflectance Ratio
San Bernardino	1500	.218
near Mtn. stream	1800	.157
Cajon Creek bed	2600	.214 - .246
Lone Pine Canyon (sun slope)	3700	.267
Lone Pine Canyon	4250	.173
Lone Pine Canyon	4800 (?)	.183

Certain difficulties were experienced in taking significant measurements. One is to obtain sufficient foliage in good illumination. As long as the instrument is not moved between the visual and infrared readings, however, the reflectance ratio will remain stable, shadow areas reducing each proportionately. Avoidance of specular reflection from leaves is a more severe problem. Specular reflection injects a varying amount of incident illumination into the readings that is not affected by the plant. This will affect the

resulting ratio. The orientation of the incident light measurement is important since the color temperature of the illumination changes when the percentage of skylight to sunlight increases. Most consistent results were obtained by taking the incident light measurement (including measurements from a reflectance standard) on the same axis as the measurement of the plant reflection.

The reflectance ratio appears to be an interesting avenue for further study of the relation of reflectance to tissue water content. It can be rapidly made with the relatively inexpensive broadband spectroradiometer described. More experience with it, however, is desirable. The stage of leaf maturity may also significantly affect the ratio, perhaps masking tissue water effects. Ratios appear to differ between plant species and varieties. To ascertain whether the ratio has utility in assessing the water content of vegetation, a sequence of measurements on a single plant specimen should be made throughout an annual cycle, with observational conditions as nearly alike as is possible.

COLOR INFRARED FILM AS A REFLECTANCE INDICATOR

Color infrared film (Kodak Ektachrome Infrared Aero, type 8443) will yield a red record when reflection of near infrared wavelengths is considerably greater than that in the visual realm. This suggests that it could have utility in making a qualitative assessment of the reflectance ratio. With proper exposure, the lower the ratio, the brighter the red.

In order that the strong infrared reflectance of plants not consistently dominate the color balance, the infrared or cyan layer of CIR film has been designed less sensitive than the others [Fritz, 1967]. For this reason, neutral subjects (with reflectance ratios approaching 1.0) tend to appear

cyan. As the reflectance ratio is lowered the density of the cyan dye will be lowered, eventually below that of the other dye layers, and various hues of red will appear. These will first be a purple red that will become brighter and more orange as the difference between the reflectances increases. When the film is used as recommended by the manufacturer, a red balance in the image appears when the VIS/IR reflectance ratio drops below approximately .250. By use of auxiliary filters which suppress the sensitivities of the yellow and magenta dye layers [Pease and Bowden, 1968], red will occur with higher reflectance ratios.

The effects on VIS/IR reflectance ratio of the chamise of Table 2 is shown in Plate 3. Unfortunately the period remaining in this project after basic observational procedures were established, did not permit an annual analysis of a specific vegetation sample. In the view in Plate 4 an increase in red balance is evident between May 4 and July 9 despite the fact that the film used for the latter image was in poor condition. This is attributed to new leaf growth which appears to more than offset any decline in water content with the advancing drought season. This is a relatively high altitude sample (4500 feet) and the effects of summer drought were not as yet fully effective.

A sequence of CIR images was made of the chaparral in Lone Pine Canyon to further note any evidence of moisture difference that might occur with site. Shown in Plates 5 and 6, these views suggest that varietal differences may be more important than drought conditions in producing a pattern of differing reds.

It should be realized that the reputation of CIR film as a diagnostic

tool in assessing plant vigor has come from observations (Fritz, Colwell, and others) showing the fact of color change in the leaves of diseased plants, rather than the cause of the color change. Until the plant substances are identified that account for the color changes detected by the film, it is not possible to predict the potential of the film for detecting moisture stress in native vegetation. The characteristics of the film that apply to the problem are summarized in the following statements.

Advantages of CIR film.

(1) It is a high-contrast medium. Color differences are thus exaggerated.

(2) Color rendition is affected by a wave band to which ordinary film is insensitive, the near-infrared. Thus, if drought typically causes a rise in reflectance in the visual band, and a drop in the near-infrared, as our observations suggest, the combined effect creates a color effect upon a three-dye-layer film greater than if only one wave band were affected.

Drawbacks of CIR film.

The utility of CIR film as an indicator is based upon the validity of reflectance change due to moisture. This needs more study. The use of CIR film has further drawbacks.

(1) Changes in the spectral composition of the illumination cannot be as easily eliminated as with electronic measurement. Standardization here would require a reference neutral reflectance or gray card be included in the image.

(2) There can be considerable variation between rolls of film that depends upon freshness, conditions of storage, and time between taking and development. A sample of film kept in warm conditions showed significant loss of general sensitivity. Freshly taken images were darker than with new film and images that remained undeveloped for a considerable time were badly deteriorated. Unless the film used at different times is reasonably close to a standard condition, results will not be comparable.

(3) Processing differences will also yield non-comparable results, although with care this problem could be held to a minimum.

(4) Time necessary for processing can be an inconvenience. If done commercially, a lag of several days almost negates utility of CIR film in assaying fuel state.

(5) Non-green components in the image also dilute results. Flowers on the chamise, for example, have a high VIS/IR reflectance ratio. From a distance they change the color aspect of the plant. Woody shrubs may exhibit a great deal of stem material which the camera and interpreter fail to resolve.

(6) Dramatic changes in color hue (compared to those perceived on standard color film, or to the unaided eye) depend not only upon proper exposure, processing, and condition of the film, but filtration. By the use of subtle but important spectral subtractions of light affecting CIR film, color differences appear that are masked without suitable filtration. Unfortunately, the filtration required for optimal color differentiation cannot be predicted in

advance. Fritz recommends a series of 69 photographs for each subject to properly bracket exposure and color differences. Obviously, further study is needed if simpler procedures are to be devised for the early detection of drought effects upon plants. Our investigation has also considered the length of the light path as a further basis for filtration, particularly for the purposes of aerial photography. This consideration complicates rather than simplifies the problem. Nevertheless, our present recommendations are given as a tentative basis for continuing observations.

RECOMMENDATIONS

A. Photography

CIR film is available commercially from most large photo dealers in the familiar 35 mm cassettes as Kodak Ektachrome Infrared Aero, Type 8443. In use, a minus-blue filter (Wratten 12 or 15) must be placed over the camera lens to reject the unwanted spectral blue light to which all layers of the film are sensitive. The manufacturer gives a film speed of ASA 100 for the film when the filter is in use. If a behind-the-lens metering system is used, however, an ASA setting of 160 should be used. The system will compensate automatically for all filtration used.

Care should be taken in ascertaining proper exposure with either system. Exposure meters, including the integrated camera systems, are adjusted to an average reflectance of 18 percent. Forests and chaparral have a lower reflectance than this in the spectral bands to which the meters are sensitive.

If readings are taken directly from them in a normal manner the result will be overexposure of the image. More accurate determinations can be made by taking readings from an 18 percent reflectance card (Eastman Kodak) which is the same as using an incident light meter. If readings are taken from the vegetation directly try closing the aperture one f-stop over that indicated. For subjects that are in full sun, a rule of thumb exposure is 1/125 sec. at f-16, or a corresponding value that will give the same exposure.

As is noted in Plate 6, auxiliary filters can extend the range of information recorded in the red record. Discrimination of information then may be made on differences of red hue and tone rather than simply between red and blue as is frequently the case when the 15 filter is used alone. One worker in Australia (Simonett, at Houston, Sept. 1968) has said that he can discriminate seven more types within a body of vegetation when an 80B auxiliary is used than when the minus-blue filtration is used alone.

Should there be desire to experiment with the enhancing auxiliary filters (actually visual-depressing), the following is a summary of information contained in Pease and Bowden (1968). There are two basic filter families that are appropriate as auxiliaries, the blue color compensation filters and the blue light balancing filters. The former are designated as CC (blue) and the latter are in the Wratten 80 and 82 groups. In general, the CC blue types will produce a more orange result than the light balancing types. Various degrees of enhancement of the infrared record are possible with either type. Table 3 lists them with exposure recommendations. The suggested ASA speeds for the overall combinations are based upon a speed of ASA 100 when the

minus-blue filter is used alone. Again, if a behind-the-lens metering system is used, simply set the camera at ASA 160 and the system will compensate for all filtration used. Since both exposure meters and integrated systems are not always accurate to the degree desirable for work with this high contrast, low latitude color material, experimentation as to the best settings should be made.

Table 3

	Auxiliary filter	Filter factor	ASA speed
For mild enhancement	82A	1.3 (1/3 stop)	90
For moderate enhancement	82B, 80D,	1.6 (2/3 stop)	64
	CC30B	2.0 (1 stop)	50
For drastic enhancement	80B, 80C, CC50B	2.7 (1-1/3 stops)	40

B. The Broadband Spectroradiometer

The use of the broadband spectroradiometer has already been described. It is recommended that a program of observations of specific plants be inaugurated to extend over at least one annual cycle. VIS/IR reflectance ratios should be determined at least once a week in order to study the change of this phenomena with seasonal changes in drought, new growth, etc.

In the case of Manzanita (A. glauca) shown in Figure 4, c. the instrument as designed will not record the apparent change that takes place deep in the near infrared. A suitable instrument could be designed around a photodiode which is sensitive in these ranges, with appropriate interference

filters delimiting the spectral band passed. The change in the reflectance of Manzanita was one of the most definitive drought-related changes encountered in the inquiry and certainly merits further investigation with an appropriately designed instrument.

CONCLUSIONS

There is little question that changes in the ratio between the visual and near infrared reflectances of plants do occur. There is considerable question, however, as to what extent these are related to the water content of the plant tissue. One question clearly needs answering. Is the low visual reflectance of healthy foliage due to water content or chlorophyll molecular structure? It is natural to assume that chlorophyll will lower the visual reflection because these are the wavelengths absorbed to carry on photosynthesis. If chlorotic vigor is the basic determinant of the VIS/IR reflectance ratio, then water content may or may not be indicated by reflectance. Rapidly dried materials, such as pine needles, which stay green in color still maintain a fairly low reflectance ratio until the green coloration disappears. This would indicate tissue water to be a secondary or at the most a partial determinant of reflectance change.

Despite these reservations, the results of this inquiry have been sufficiently suggestive to merit a substantive program of observation, both electronic and photographic, over an annual cycle and using a variety of plant samples. It is suggested that several sample chaparral plants be chosen, and careful records of soil moisture, temperature, and reflectance be kept. Upon this data more definitive conclusions regarding the relationship of reflectance and fuel state can be drawn.

APPENDIX A.

THE PEASE BROADBAND SPECTRORADIOMETER

This instrument is useful for making rapid comparisons of the visual spectral band with the near infrared. It consists of two sensors, a selenium cell (International Rectifier type B2) to measure the visual and a silicon solar cell (International Rectifier #S1020GE10PL) to measure the near infrared. The silicon cell is placed behind a light filter with a shortwave cutoff at 700nm. A plastic filter was used, obtained from the Edmund Scientific Company of Barrington, New Jersey. Two selenium cells were cemented to the front or light side of the plastic filter and placed on either side of center to permit light to pass through to the silicon cell. Two selenium cells were used in order that the visual band develop electrical energy proportionate to the energy available in this waveband. Selenium cells are far less efficient energy converters than are silicon cells. Outputs of the sensor cells are selectively fed to the recording meter by means of a single pole double throw switch. Resistance shunts across either sensor can be used to trim outputs to desired visual/infrared ratios. A 2200 ohm shunt was used across the visual sensors in one version of the instrument to calibrate it to energy available to two 300 nm. wave bands (400-700 and 700-1000) in sunlight. Readout is obtained from a 0-100 microampere Weston meter (#1931T), the low internal resistance (538 ohms) of which leaves electrical energy closely proportional to light energy, the relationship being linear.

The visual selenium sensor peaks at 550 nm. while the combination of light filter and silicon sensor peaks at 800 nm. In typical sun and sky illumination this gives approximately 1.8 times as much energy available to the visual sensor as to the infrared sensor (graph 1.). Sun and skylight in combination have close to a 6000^{o}K color temperature. With other color

temperatures, however, different ratios apply. For a 2900°K incandescent lamp, for example, the ratios are approximately 3 to 1 in favor of the infrared. The Vis/IR ratio changes from 1.8 to .30. With the aid of graph 2 the instrument can thus be used to determine the color temperature of the light.

For purposes of energy comparison, it is useful to think of the visual band as being all energy available between 400 and 700 nm while the near infrared is the energy between 700 and 1000 nm. This gives two bands of the same width. However, these bands do not exactly coincide with the sensitivities of the sensors. The selenium sensor senses some solar energy below 400 nm. and declines rapidly between 600 and 700 nm. The silicon sensor rises rapidly at 700 but trails off in sensitivity above 950 nm to an upper threshhold at about 1100 nm. Factors to convert the energy available to the sensors to the 300 nm band energies noted above depends upon the black body (color) temperature of the illumination source. Ratios of the energy available in the 300 nm. visual to that in the near infrared wavebands is also shown in Graph 2. It will be noted that it varies only a moderate amount from the ratios for energy available to the sensors. Factors for converting sensor energies to 300 nm. band energies are shown in graph 3. They are listed according to the VIS/IR ratio but could as well be according to the color temperatures of the illumination.

To convert the meter readings to radiant energy, each microampere should be considered as about 20 microwatts/ cm^2/ 300 nanometers.

In general construction, the broadband radiometer consists of the sensor cell (sensors and filters) secured to the end of a 14 inch length of 2 inch

I. D. tubing. The meter is mounted above (Plate) and a pistol grip placed below. The visual-IR switch is placed in a convenient position by the pistol grip. A release-on pushbutton switch is placed in the handle to short out the meter when not in use. The self-damping thus obtained protects the meter from shock.

Figure 5. CALIBRATION OF THE BROADBAND SPECTRORADIOMETER

Sensor sensitivity curves are plotted in theoretical emission curves for black body illumination sources of different color temperatures. The curves of energy available to the selenium or visual sensor is on the left and that for the silicon or infrared sensor is on the right. The shaded areas represent energy emitted in discrete 300 nm wavebands (visual 400-700 nm and infrared 700-1000 nm). It is to be noted that the ratio of energy available to the two sensors virtually reverses as the color temperature drops from 6000°K to the 2900°K of an incandescent lamp. The energy available to the sensors in sunlight illumination is close to but not exactly the same as that for 6000°K. The difference is primarily due to the lack of solar energy between 300 and 400 nm.

W = radiant energy in watts

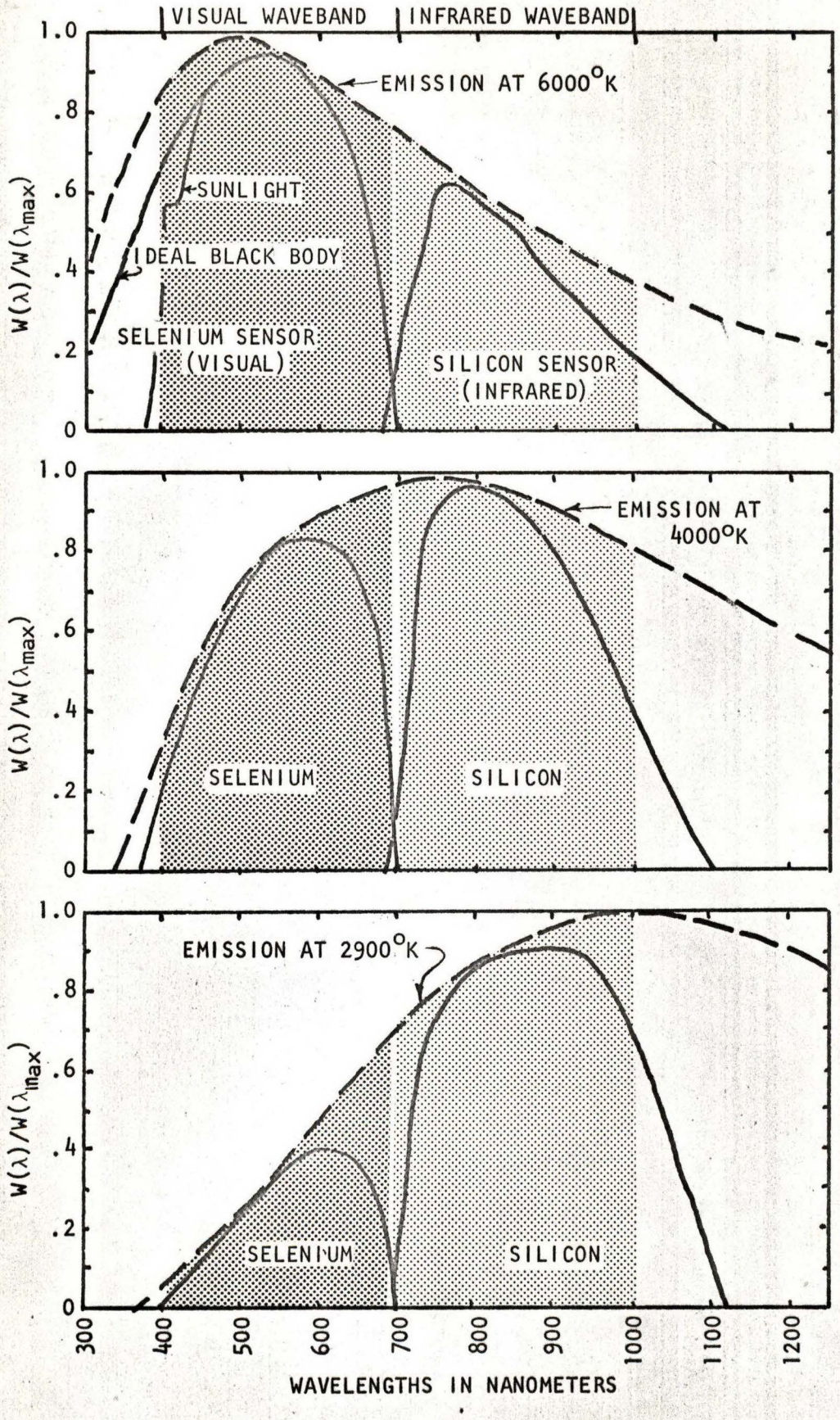

VISUAL WAVEBAND
INFRARED WAVEBAND
EMISSION AT 6000°K
SUNLIGHT
IDEAL BLACK BODY
SELENIUM SENSOR (VISUAL)
SILICON SENSOR (INFRARED)
EMISSION AT 4000°K
SELENIUM
SILICON
EMISSION AT 2900°K
SELENIUM
SILICON
W(λ)/W(λmax)
1.0
.8
.6
.4
.2
0
300
400
500
600
700
800
900
1000
1100
1200
WAVELENGTHS IN NANOMETERS

FIG. 5.

Figure 6. CALIBRATION OF THE BROADBAND SPECTRORADIOMETER (CONTD.)

a. This graph plots VIS/IR ratios determined from a sequence of curves like those illustrated in Figure 5. The solid line compares areas within the two sensor curves (as a VIS/IR ratio) against the color temperature that yields each ratio. Empirically measured sources of known temperature fall close to this line. A 2900°K incandescent electric lamp plots at A. A 3400°K photoflood lamp locates at B. Points C and D are measurements made with the broadband spectroradiometer of the sun when the ISCO indicated color temperatures of 4200°K and 5300°K, respectively. Measurements of a noonday sun plus sky illumination plot at point E close to the line.

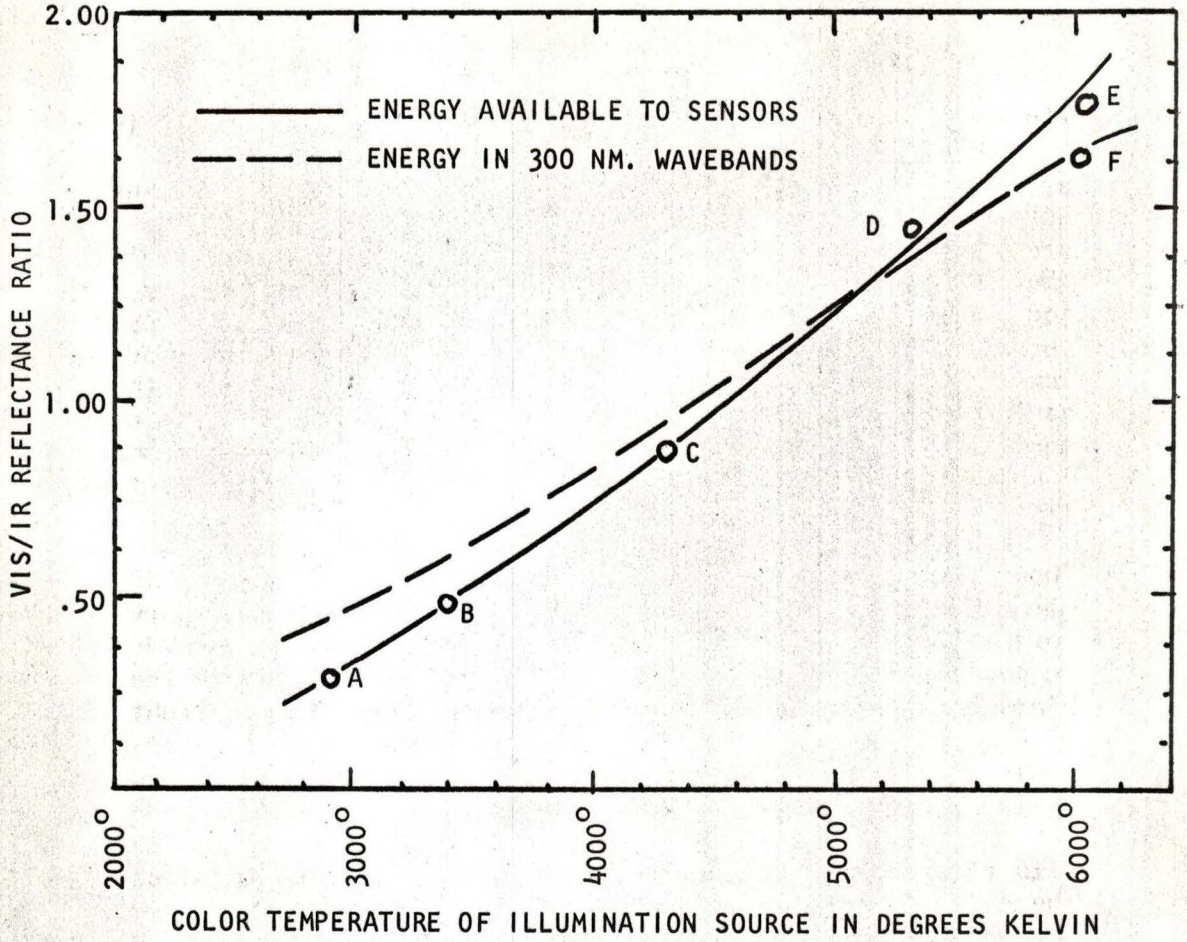
The dashed line plots the VIS/IR ratios of the discrete 300 nm wavebands according to the several black body emission curves. For a 6000°K curve the ratio should plot at F. However, due to the divergence of the sunlight curve from the theoretical black body emission curve, the waveband ratios for sunlight plot at E. This is convenient, for when the instrument is used with sunlight illumination, the sensor ratios can also be considered as the ratios of the 300 nm wavebands.

With this chart, the spectroradiometer can be used to ascertain the color temperature of a black body light source.

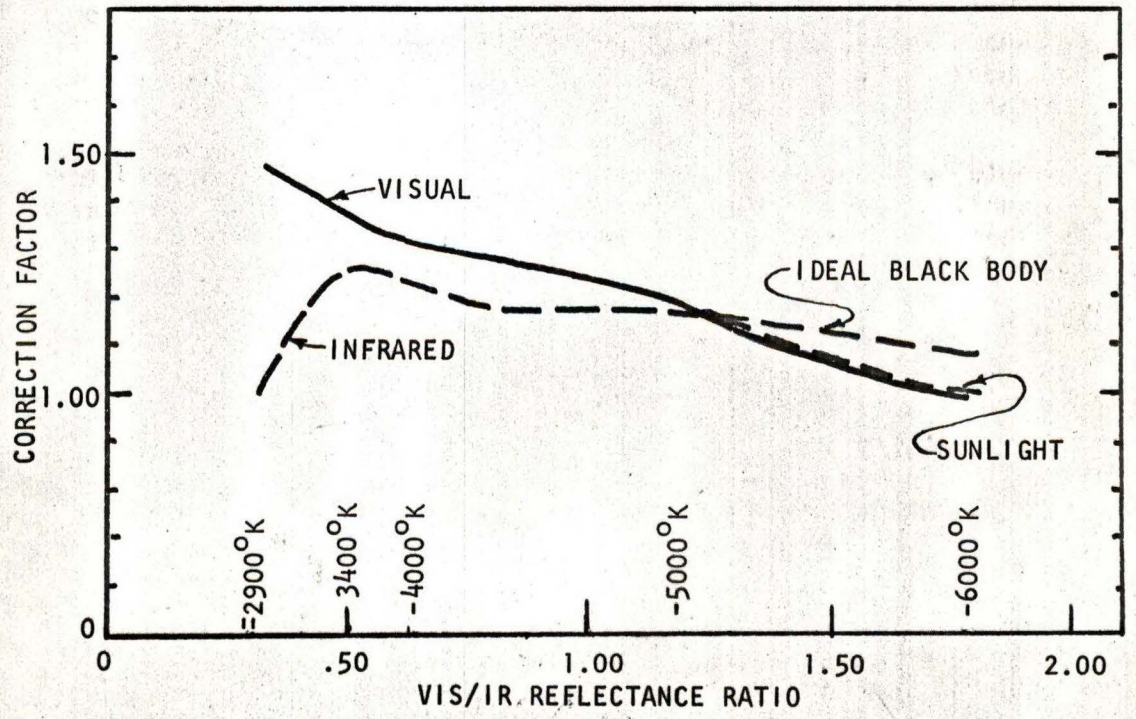
b. Readings obtained with the broadband spectroradiometer will be readings of energy available to the respective sensors. To convert these to energy in the two 300 nm wavebands, correction factors shown in the accompanying graph should be used. The solid line should be used for the visual waveband and the dashed line for the infrared.

Note that for light sources near 6000°K the correction factors for sunlight (sun and sky) are the same for visual as for infrared. When the instrument is used with sunlight illumination in the middle hours of the day, no correction factor is needed.

FIG.6.


2.00
1.50
1.00
.50
VIS/IR REFLECTANCE RATIO
ENERGY AVAILABLE TO SENSORS
ENERGY IN 300 NM. WAVEBANDS
A
B
C
D
E
F
2000°
3000°
4000°
5000°
6000°
COLOR TEMPERATURE OF ILLUMINATION SOURCE IN DEGREES KELVIN

a.


1.50
1.00
0
CORRECTION FACTOR
VISUAL
INFRARED
IDEAL BLACK BODY
SUNLIGHT
=2900°K
3400°K
-4000°K
-5000°K
-6000°K
0
.50
1.00
1.50
2.00
VIS/IR REFLECTANCE RATIO

b.

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Fritz, Norman L., 1967. "Optimum Methods for Using Infrared Sensitive Color Film," Photogrammetric Engineering, Vol. XXXIII, Number 10 (October), pp. 1128-1138.

Pease, R. W. and Bowden, L. W., 1968. "Making Color Infrared Film a More Effective High Altitude Remote Sensor," Remote Sensing, an Interdisciplinary Journal, Vol. 1, (in press).

Plate 1. THE PEASE BROADBAND SPECTRORADIOMETER

Selenium and silicon sensors are at the rear end of the tube, the silicon behind a filter that cuts off all light with wavelengths shorter than 700 nm. Outputs are fed to a microammeter, the low internal resistance of which permits a conversion factor of approximately 20 microwatts/cm^2/300 nanometers for each microampere over the entire scale. The toggle switch selectively feeds the input of the two sensors to the meter. The red pushbutton on the handle shorts the meter when not in use in order that self damping reduce shock damage. The removable cap on the front end of the tube is an incident light screen of known visual and IR transmittance that is used in converting meter readings to reflectance readings.

Plate 2. SPREAD OF LEAVES FOR MEASURING REFLECTANCE PHOTOGRAPHED WITH COLOR INFRARED FILM

For the best reflectance measurements, a mass of leaves is spread upon a non-reflective backing with as little non-leaf surface exposed as possible. The leaf reflectances are measured as soon as possible after plucking (in the field if possible). Measurements made on the plant will usually yield lower values due to the amount of shadow that must be included.

In the accompanying color infrared photograph, healthy dark green Yellow Pine needles are on the left. Smog mottled, yellowish green needles are on the right. The brush top center are immature needles, new this season.

PLATE 1.

PLATE 2.

Plate 3. DROUGHT AND THE COLOR INFRARED RECORD

These two CIR photographs were made within an hour of each other in the Cajon Pass-Lone Pine Canyon area. Both were taken on the same roll of film, received the same initial processing, and were processed together in the making of the color prints with no change in color balance. The top view is Chamise (Adenostoma fasciculatum at 1800 feet in Cajon Canyon. Only a little red color shows. Do not confuse the Chamise with the brightly colored Yerba Santa (Eridicuton trichocalyx) at the bottom of the picture typical of the strong IR record that is obtained from glaborous-leafed plants. The lower photo is Chamise taken at an elevation of 5000 feet in Lone Pine Canyon. The red infrared record is much more prominent.

Without further tests it is impossible to say whether this difference is due to water content or maturity of the leaves. As the presence of blooms indicate, the Chamise at higher elevation was still in an earlier seasonal phenological stage.

Dilution of color due to such causes as bloom or woody stems makes evaluation of the color of distant CIR shots difficult.

PLATE 3.

Plate 4. SEASONAL CHANGE IN THE COLOR INFRARED RECORD

These two CIR photographs of a slope below Crestline, California indicate that changes do occur in the visual/infrared reflectance ratio with the season. Both were made at approximately 2 PM with as close as possible to the same type of atmosphere conditions. The upper photo was made May 4 while that below on July 9. Both used identical filters, the Wratten 12 recommended by the manufacturer of the film.

Although the film used for the lower photo had experienced considerable deterioration from age and storage under warm conditions, it still indicated a considerably stronger infrared record in July than May. This is in spite of greater drought conditions at the later date. The simplest explanation would be that more new leaf growth was present in July than in May. If this be so, other factors can more than offset any changes in the VIS/IR reflectance ratio brought about by drought, particularly when CIR film is to be used as the indicator.

PLATE 4.

Plate 5. COLOR INFRARED FILM AND CHAPARRAL

Two views of a chaparral site in Lone Pine Canyon (cameras at 3700 feet) with the upper photo in natural color and the lower made with color infrared film (Wratten 15 filter only).

In the CIR view, the Chamise and Cerocarpus show very little selective infrared reflectance. A high percent of exposed woody stems and the orientation of leaves in the Cercocarpus, may be responsible for this. The better foliated Manzanita (A. glauca) shows some red, although the glaucus covering neutralizes the visual-IR reflection differences when leaves are not oriented normally to the optional axis. The bright red spots are Sumac (both Rhus ovata and laurina) the glaborous leaves of which yield a good record from all angles.

Varietal difference in leaf morphology and orientation appear to be strong determinants of the patterns of infrared record when a vegetation cover is viewed en masse.

PLATE 5.

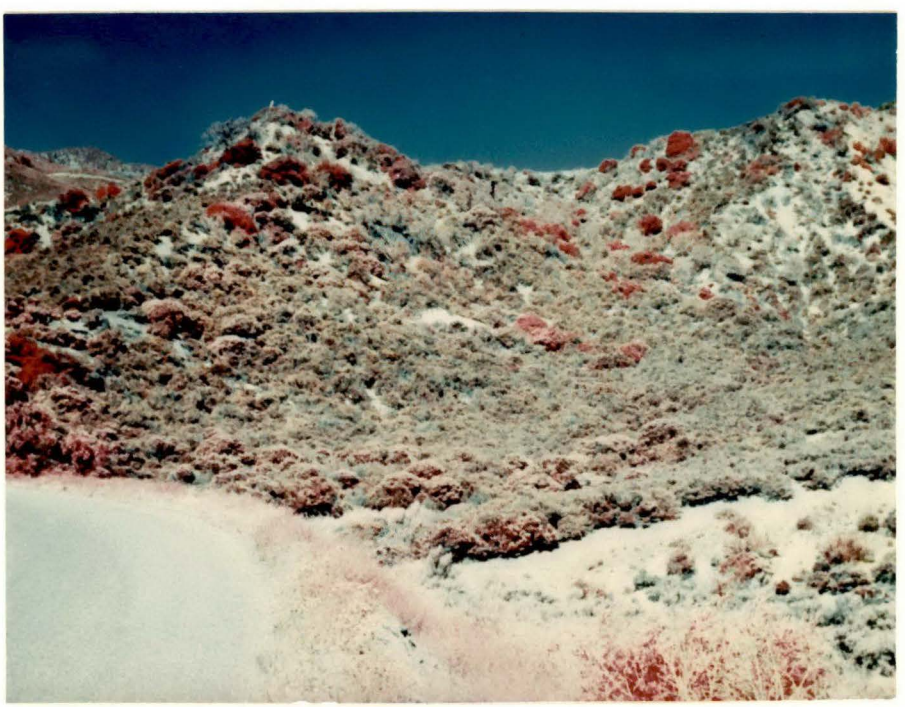

Plate 6. THE EFFECTS OF AUXILIARY ENHANCING FILTERS ON THE INFRARED RECORD

By means of filters used in addition to the basic CIR minus-blue filter (the Wratten 12 or 15) the VIS/IR reflectance ratio threshold at which red begins to appear can be raised.

a. A natural color view across Lone Pine Canyon which shows various chaparral forms. Chamise and Manzanita predominate on the flat, except for oak thicket on left (Q. dumosa). Chamise also predominates in almost pure stands on the lower ends of the opposing ridges, but the larger shrubs such as Sumac of the higher slopes extend down the canyons between.

b. When the Wratten 15 filter is used alone only the Sumac and oak show a strong red record, possibly due to the glaborous nature of their leaves.

c. When a CC30B filter is added to the 15, differences within the chamise become apparent, that in the valley bottom producing a better IR record than on the distant lower ridges.

d. The use of an 80B as an enhancing auxiliary increases somewhat the red record and changes the color balance. It yields approximately the same information as does the CC30B.

The distant slopes were completely burned in early September 1968.

PLATE 6.

a.

b.

PLATE 6 (CONTD.)

c.

d.

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